THE CLASSIFICATION OF STARS ACCORDING TO THEIR TEMPERATURE AND CHEMISTRY.

I.

ALTHOUGH the observations made by Fraunhofer in 1814 first indicated that the spectra of stars were not all of the same character, it was the more systematic observations of Rutherfurd and Secchi fifty years later which revealed the fact that the different varieties of stellar spectra were, generally speaking, associated with stars of different colours. The stars with fluted spectra, for instance, were generally found to be red; those resembling the sun in having abundant metallic lines were yellowish; while those in which the chief absorption was due to hydrogen were white. Closely following these observations came Zöllner's suggestion that the spectra might indicate the relative ages of the stars, and that the yellow and red stars were older and cooler than the white ones, thus giving birth to the now generally accepted view that the different kinds of stellar spectra represent different temperature stages in the evolution of more or less similar masses of matter. More direct evidence as to temperature differences was brought forward shortly after by Ångström, who directed attention to the probability that the flutings characteristic of the red stars originated in chemical compounds, and pointed out that the occurrence of flutings in such a star as Betelgeuse might be taken as an indication that the temperature of the star was sufficiently reduced to permit the formation of chemical combinations. Subsequent researches have shown that all flutings do not proceed from compounds, but the fact remains that in laboratory experiments flutings are only produced by relatively cool vapours and gases, and their presence in the spectrum of a star may therefore be still accepted as evidence of greatly reduced temperature. The broad distinction between the spectra of cool and hot stars was thus early recognised, but it remained to establish the sequence of temperature in the stars characterised by line spectra.

It was next pointed out by Sir Norman Lockyer in 1873 [1] that the spectrum of the sun was intermediate between the more complex fluted spectrum of the red stars and the simpler line spectrum of the white ones, and further that the great development of the blue end of the spectrum in the white stars, as contrasted with stars like the sun, afforded strong presumptive evidence that the white stars were the hotter. Experiments had, in fact, shown that the continuous absorption exerted by certain gases was restricted to the most refrangible part of the spectrum when the density was low, and advanced gradually into the visible spectrum as the pressure was increased. Utilising this criterion, it thus appeared that the hotter a star the simpler was its spectrum, and it was pointed out also that the metallic elements seemed to make their appearance in the order of their atomic weights. As a working hypothesis, founded primarily on results obtained in solar inquiries, it was suggested that in the atmospheres of the sun and stars various degrees of dissociation were at work, so that in some cases the atoms which compose what at terrestrial temperatures we distinguish as metals, metalloids, and compounds, were prevented from coming together. Hence "the so-called elements not present in the reversing layer of a star will be in course of formation in the coronal atmosphere, and in course of destruction as their vapour densities carry them down; and their absorptions will not only be small in consequence of the reduced pressure in that region, but what absorption there is will probably be limited wholly or in great part to the invisible violet end of the spectrum."

Secchi's classification was, of course, made quite independently of such considerations as to temperature; but being based to a great extent on the colours of the stars associated with the different spectra, the numerical sequence of his four well known types is more or less in accordance with the probable temperature gradation.

Vogel [2] was the first to propose a classification professedly depending upon the supposition that the spectrum is indicative of the phase of development which a star has reached, and making use of the condition of the blue end of the spectrum as a guide to the temperature conditions. In stars of his class i. the more refrangible portions of the spectrum are of conspicuous intensity, in class ii. the blue and violet are weaker, while in class iii., which includes Secchi's third and fourth types, this part of the spectrum is described as being strikingly feeble. This is, indeed, the principal feature which is common to the several subdivisions of each of the three classes, and, apart from such possible resemblance, it is difficult to understand, for example, how stars so widely different as Arcturus and the bright line stars of the Wolf-Rayet group could have been brought together in the same class. Thus, although the idea underlying the classification was that of decreasing temperature in passing from the first to the third class, there was no adequate attempt to define the successive positions of the various subclasses on the descending scale of temperature.

Another idea was put forward in 1887 by Sir Norman Lockyer in connection with the meteoritic hypothesis.[1] Hitherto the generally accepted view as to stellar evolution had started with the assumption that all the stars were intensely hot to begin with, and that all further development was brought about by reduction of temperature; but it was objected that all bodies in the universe cannot be finished suns in the ordinary sense, and that the old view took no account of the processes of manufacture from nebula to sun. It was then suggested that the progress of stellar development was from comparatively cool nebulæ, through uncondensed "stars" of rising temperature, to the hottest stars, with a subsequent decline, through stars like the sun, to planetary conditions. On this modified basis a new classification was proposed in which seven groups were found sufficient to include the data depending on the visual observations, which were then practically all that were available. Some such arrangement of the stars in two series is, in fact, demanded by thermodynamical principles, since a mass of gas condensing under the influence of gravitation must continue to rise in temperature so long as it remains in a condition approaching that of a perfect gas, and Prof. Darwin has shown that a condensing swarm of meteorites would behave in a similar manner.

The magnificent success which soon after attended Prof. Pickering's photographic application of Fraunhofer's method of studying stellar spectra by means of an objective prism, and the subsequent use of the same form of instrument by Sir Norman Lockyer and others, provided data for a far more searching inquiry into the processes of stellar development. Conclusions as to the relative temperatures of the stars could now be more certainly drawn from the extension of their spectra towards the ultra-violet, as shown by the photographs, and the chemical changes accompanying the variation of temperature from star to star could be much more accurately observed.

In a discussion of the photographic spectra of 171 of the brighter stars, Sir Norman Lockyer [2] again found it necessary to arrange the stars in an ascending and a descending temperature series, as was previously the case when dealing with the visual observations, and the general sequence of events demanded by the meteoritic hypothesis was therefore so far confirmed. The classification into seven groups was still retained, but various subgroups were introduced in order to include the finer shades of difference revealed by the photographs.

At this stage of the inquiry many of the stellar lines, especially in the case of the hotter stars, had not been identified with terrestrial spectra, and further progress resulted rather from laboratory than from observatory work. Sir William Ramsay's discovery of terrestrial helium permitted a complete study of the spectrum of that element, and provided a most satisfactory explanation of many of the previously unknown lines appearing in the spectra of some of the white stars, and other lines usually associated in the stars with those of helium were subsequently traced to oxygen, nitrogen, carbon, and silicium.

But there was still another great class of outstanding lines, occurring in such stars as Sirius and α Cygni, for which chemical origins could not be certainly assigned on current principles. Continuing his researches, dating from

[1] *Phil. Trans.*, vol. clxiv., p. 492 (1874), and *Comptes rendus*, vol. lxxvii. p. 1357 (1873).
[2] *Ast. Nach.*, vol. lxxxiv. (1874), p. 113.

[1] Roy. Soc. *Proc.*, vol. xliii. p. 117.
[2] *Phil. Trans.*, vol. clxxxvi. A 1893), pp. 675-726.

1879, Sir Norman Lockyer[1] made the important discovery that several of these "unknown" stellar lines were coincident with lines of iron which were enhanced in brightness in passing from the arc to the spark spectrum. What is meant precisely by "enhanced lines" may be gathered from Fig. 1, and the first idea of their relation to stellar spectra is well brought out in Fig. 2.

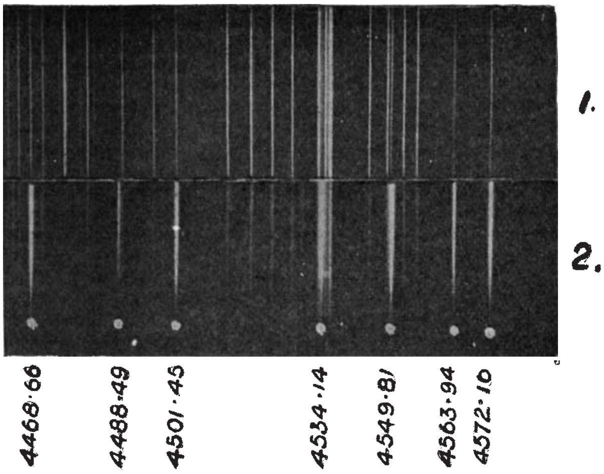

FIG. 1.—Illustrating enhanced lines of titanium; (1) arc, (2) spark.

The laboratory experiments suggested that in a space heated to the temperature of the hottest spark, and shielded from the effects of a lower temperature, the spectrum of iron would consist of these enhanced lines alone, and the outcome of the investigation was, in fact, to show that this condition is realised in the stars which are judged to be very hot by the extension of their spectra into the violet. Thus in α Orionis the continuous spectrum in the violet is feeble, and the arc lines and flutings appear without the enhanced lines; in α Cygni the violet radiation is more intense, and the enhanced lines are relatively much stronger than the arc lines; while in Rigel, with still stronger violet radiation, the enhanced lines appear in the absence of the arc lines. At a still higher stage, represented in the diagram by γ Orionis, the metallic lines have disappeared altogether, and are replaced by lines chiefly due to gases.

In a subsequent paper[2] it was shown that similar results were obtained in the case of other elements, and the presence or absence of enhanced lines, or their intensities as compared with those of the arc lines, appeared to afford a ready means of arranging stars at certain stages in order of temperature independently of a special study of the violet radiation. Adopting this mode of bringing together stars of approximately the same mean temperature, it was found, as before, that at each stage the stars were divisible into two groups, and that these groups naturally fell into two series, in each of which there was an almost unbroken sequence of changes in the line spectra. As determined in this way, stars of one series differ from those of the other at the same stage of heat:—"(1) in the greater continuous absorption in the violet or ultra-violet, (2) in the generally greater intensity and breadth of the metallic lines, (3) in the smaller thickness of the hydrogen lines, (4) in the greater thickness of the helium lines at those stages in which they are visible." The differences indicated in (2) and (3) are well illustrated by the comparison of the spectra of Sirius and α Cygni given in Fig. 3.

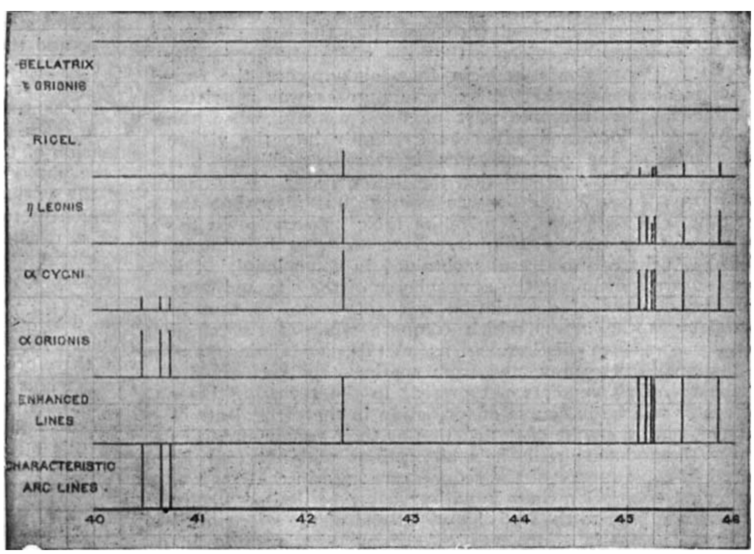

FIG. 2.—Illustrating the gradual replacement of arc lines of iron by enhanced lines in stars of increasing temperature.

[1] Roy. Soc. *Proc.*, vol. lx. p. 475 (1896). [2] *Ibid*, vol. lxi., pp. 148–209 (1897).

It is to be noted that while the *relative* intensities of the arc and enhanced lines of the same metal are the same in both stars, thus indicating probable near equality of temperature, the metallic lines generally are weaker in Sirius than in α Cygni, while the lines of hydrogen behave in an exactly opposite manner.

The differences between the two series were explained by supposing, as before, that one of them comprises stars of increasing temperature and the other those which are becoming cooler. On the meteoritic hypothesis, stars of the first series would still be in the state of uncondensed swarms, and the greater thickness of effective absorbing vapours would account for the increased continuous absorption at the violet end of the spectrum, as well as for the greater thickness of the metallic lines, as compared with those stars in which a photosphere has been formed.

In 1899, in view of the fruitful results of the continued investigation of enhanced lines in relation to the stars, Sir Norman Lockyer[1] concluded that the time had arrived for a complete revision of the nomenclature of the stellar groups, and a more extensive definition of their chemical peculiarities. This new classification, in a slightly revised form, is fully stated and applied to the spectra of 470 of the brighter stars in a recent publication of the Solar Physics Committee.[2] On account of divergences of opinion among those engaged in these investigations, the same type of spectrum was referred to differently numbered groups in the various classifications which had been previously proposed, and to avoid the confusion to which this gave rise the use of numbers was entirely dispensed with. The idea underlying the new nomenclature cannot be better stated than in the words of the author, namely:—"As we know beyond all question that a series of geological strata from the most ancient to the most recent brings us in presence of different organic forms, of which the most recent are the most complex, it is natural to suppose that the many sharp changes of spectra observed in a series of stars from the highest temperature to the lowest, brings in presence of a series of chemical forms which become more complex as the temperature is reduced. Hence we can in the stars study the actual facts relating to the workings of inorganic evolution on lines parallel to those which have already been made available in the case of organic evolution. If then we regard the typical stars as the equivalents of the typical strata, such as the Cambrian, Silurian, &c., it is convenient that the form of the words used to define them should be common to both." An adjectival form ending in *ian* was therefore suggested.

[1] Roy. Soc. *Proc.*, vol. lxv. p. 186.
[2] "Catalogue of 470 of the Brighter Stars, classified according to their Chemistry." (London: H.M. Stationery Office, 1902.)

Generally, if the typical star is the brightest in the constellation to which it belongs, the Arabic name is used as a root; if the typical star be not the brightest, the name of the constellation is used in a similar manner. Thus we have *Antarian* from Antares, *Alnitamian* from Alnitam, *Taurian* from ζ Tauri, *Piscian* from 19 Piscium, and so on. In this way the names given to the various groups have very definite associations, and will doubtless be found much more convenient than the old confusing numbers and letters, even for the mere sorting of spectra into similar groups.

but when its presence is manifested by enhanced lines the prefix "*proto*" is added, the idea being that a substance reduced to the state in which it gives such lines is subjected to some sort of molecular simplification resulting from the dissociating effects of increased temperature. In the case of hydrogen, the proto-lines have not yet been even partially produced in laboratory experiments, but that they are really due to hydrogen is sufficiently demonstrated by the "series" connection of their wave-lengths with the wave-lengths of the more familiar lines of that element. Silicium exhibits four distinct line spectra under different conditions, and it has been found convenient to refer to these in numbered groups. It would be out of place here to reproduce all the minute details of the new classification, but referring only to the most characteristic lines of the various stellar groups, the classification may be shortly stated as follows, the prefix "p" signifying "proto":—

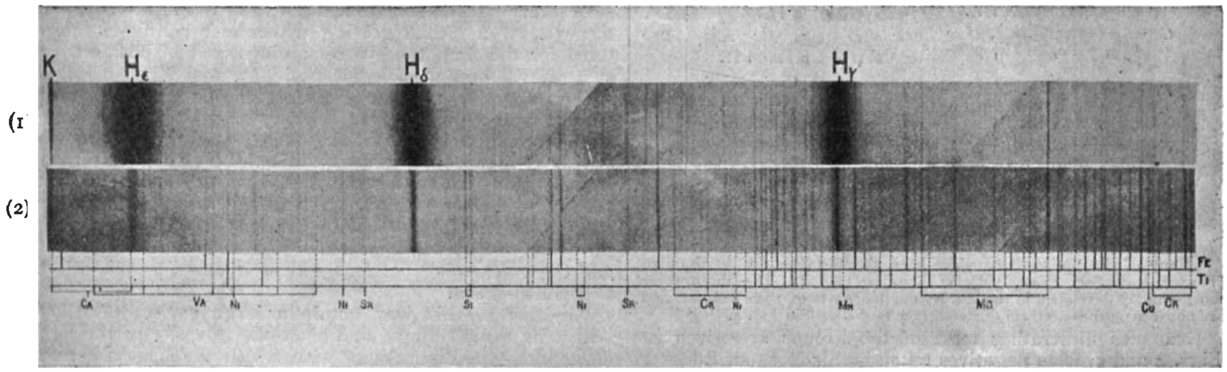

FIG. 3.—Spectra of (1) Sirius (decreasing temperature) compared with that of (2) α Cygni (increasing temperature). The chemical origins indicated are those depending upon coincidences with enhanced lines.

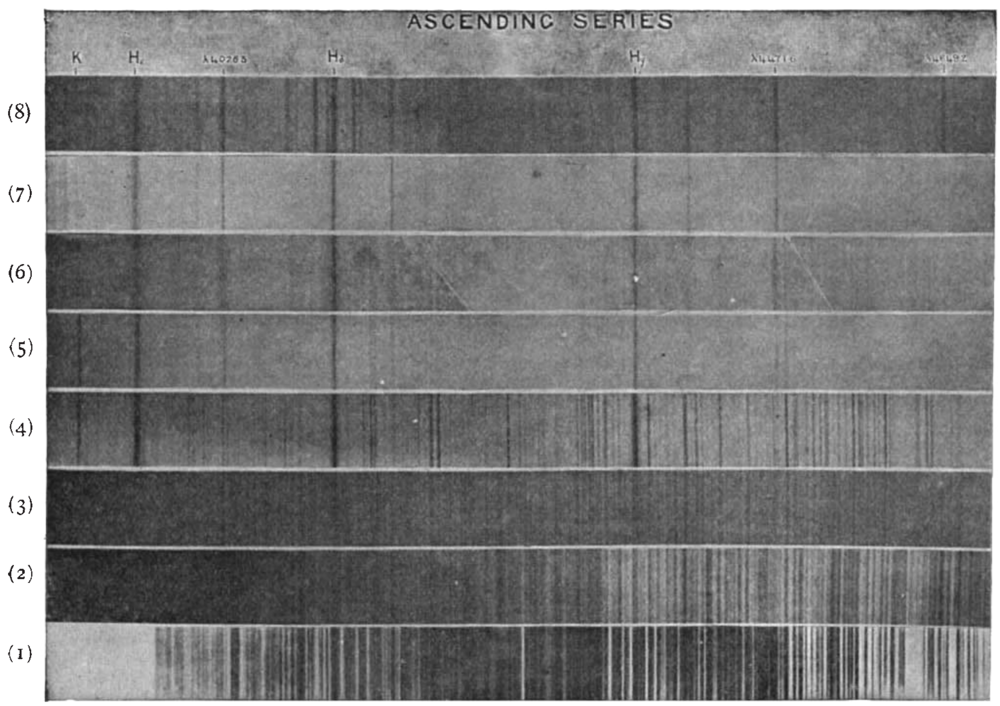

FIG. 4.—Stars of increasing temperature:—(1) α Orionis (Antarian); (2) α Tauri (Aldebarian); (3) α Persei (Polarian); (4) α Cygni (Cygnian); (5) β Orionis (Rigelian); (6) ζ Tauri (Taurian); (7) γ Orionis (Crucian); (8) ε Orionis (Alnitamian).

Bearing in mind the important distinction to be drawn between enhanced lines and the ordinary arc lines of a metal, a new term was found necessary for the proper chemical definition of several of the groups. When a substance is represented by lines which have their greatest development in the arc spectrum its ordinary name suffices;

Argonian (γ Argûs).—H, p H.

Alnitamian (ϵ Orionis).—H, He, λ4649, Si IV.

Proto-metallic lines relatively thick, hydrogen relatively thin.	*Proto-metallic lines relatively thin, hydrogen relatively thick.*
Crucian (α Crucis).—H, He, Ast, O, N, C.	*Achernian* (α Eridani).—Same as Crucian.
Taurian (ζ Tauri).—H, He, p Mg, Ast.	*Algolian* (β Persei).—H, p Mg, p Ca, He, Si II.
Rigelian (β Orionis).—H, p Ca, p Mg, He, Si II.	*Markabian* (α Pegasi).—H, p Ca, p Mg, Si II.
Cygnian (α Cygni).—H, p Ca, p Mg, p Fe, Si II., p Ti, p Cr.	*Sirian* (α Canis Maj.).—H, p Ca, p Mg, p Fe, Si II.
Polarian (α Urs. Min.).—p Ca, p Ti, H, p Mg, p Fe, Ca, Fe, Mn, Si I.	*Procyonian* (α Canis Min.).—Same as Polarian.
Aldebarian (α Tauri).—p Ca, Fe, Ca, Mn, p Sr, H, Si I.	*Arcturian* (α Boötis).—Same as Aldebarian (includes the Sun).
Antarian (α Scorpionis).—Flutings of manganese,[1] and many metallic lines.	*Piscian* (19 Piscium).—Flutings of carbon and many metallic lines.
[Nebulæ.]	[Dark Stars.]

[1] Many of the flutings have since been shown to be due to titanium [Fowler, Roy. Soc. *Proc.*, vol. lxxiii. p. 219 (1904)]. The flutings are most strongly developed in the less refrangible parts of the spectrum, and are not seen in the spectrum of Betelgeuse reproduced in Fig. 4.

Examples illustrating most of the groups are given in Figs. 4 and 5, from negatives taken by Sir Norman Lockyer and his assistants at the Solar Physics Observatory. These bring out very clearly the gradual simplification of the spectrum in the first series as the temperature rises, and the increasing complexity in the second series as the temperature falls. On the dissociation hypothesis, we have first to deal chiefly with relatively cool metallic vapours, which, as the temperature rises, are brought by *dissociation* to the proto-metallic stage, and finally to the gaseous condition represented by hydrogen and helium; then, through subsequent cooling, *association* begins and produces somewhat similar changes in inverse order.

A. FOWLER.

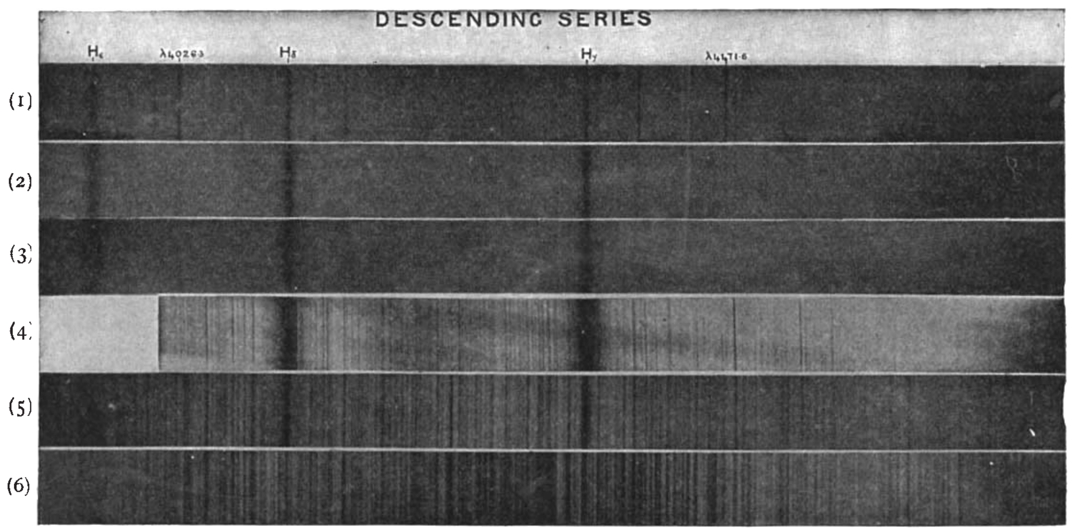

FIG 5.—Stars of decreasing temperature:—(1) γ Orionis (Crucian); (2) β Persei (Algolian); (3) α Pegasi (Markabian); (4) α Canis Majoris (Sirian); (5) α Canis Minoris (Procyonian); (6) α Boötis (Arcturian).

RECENT IMPROVEMENTS IN THE DIFFRACTION PROCESS OF COLOUR-PHOTOGRAPHY.[1]

THE fundamental principles of the diffraction process of colour-photography will be found in my earlier papers on the subject.[2] In brief, the method consists in preparing by photographic means a picture in which the areas which are to appear coloured are represented by diffraction gratings of various spacings. A grating ruled on glass, when combined with a convex lens and directed towards a lamp flame or other source of light, forms diffraction spectra in the focal plane of the lens. If the pupil of the eye is brought into the red portion of one of these spectra, we perceive the entire surface of the grating illuminated in red light, since every portion sends red light, and red light only, into the eye. If a second grating with closer ruling is substituted for the first, the eye remaining fixed in position, the spectra will occupy different positions, and if the pupil of the eye occupies, say, the green region of one of them, this grating will appear green. If the two gratings are placed side by side, and overlapping one another, the one will appear red, the other green, while the overlapping region, since it sends both red and green light to the eye, appears yellow (secondary yellow). If a third grating of still finer spacing is now placed before the lens, partly overlapping the other two, it will appear illuminated in blue-violet light, and the overlapping portions will be coloured purple, white, and bluish-green.

We may in this way obtain a large variety of colour with only three rulings, and since the intensity of the light depends on the distinctness with which the lines are ruled or photographed, light and shadow can be obtained solely by the presence of the diffracting lines. The portions of the plate on which they are absent send no light to the eye, and appear black.

A full description of the method by which photographs showing the colours of the original object were prepared will be found in the papers above referred to.

The earlier experiments were made with very imperfect gratings, the periodic errors of which caused the pictures to show vertical bands of colour. During the past winter I have ruled gratings of various description on one of the Rowland engines, and continued the experiments of five years ago.

This machine was designed to rule 14,438 lines to the inch, but by employing larger cams, which cause the pawl to skip a specified number of teeth, it may be made to rule at the rate of 7219, 4812, 3609, and so on. Calculations showed that gratings ruled on this machine with cams which advanced the toothed rim of the large wheel five, six, and seven teeth respectively would be suitable, that is, would have the relative spacings necessary to produce white when they were superposed.

To illustrate the principle of the colour synthesis, a glass plate was ruled with the three spacings, the ruled squares overlapping as shown in Fig. 1*a*. The areas appeared coloured as indicated when the plate was placed in front

[1] Paper read before Section A of the British Association at the Cambridge meeting by Prof. R. W. Wood.

[2] Wood, "Application of the Diffraction Grating to Colour-photography" (*Phil. Mag.*, April, 1899); "Diffraction Process of Colour-photography," (NATURE, vol. lx. p. 199, 1899).